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Structural Assessment via FEA of Bonded Steel Structures using Fiber Reinforced Epoxy Adhesive

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(Abstract) This paper presents a numerical study using FEM of adhesively bonded steel beams under three point bending. Previous studies done by Hashim had examined the behavior of pure adhesive layers experimentally and by FEM, and it was found that the FE analysis showed a good accuracy with respect to the experimental test which was adopted to minimize the efforts and the cost. Accordingly, in the present analysis using FEM was the major technique to investigate the possibility of improving the properties of the adhesive layers by enhancement using fillers like fiber reinforcements. Therefore, the authors focused on the improvement of the characteristics of the reinforced adhesive layers in order to improve the mechanical response of the adhesively bonded beam. To elucidate the effectiveness of the advantages of the fiber reinforcement and its impact on the whole bonded structure behavior, interface coefficient for the adhesive layer was estimated for both stresses and deflections and compared for both bonded and solid beams (welded). Due to complication of studying the welded structures because of the residual and thermal stresses, a comparison by considering the welded beams as solid one for simplicity is proposed. The numerical simulations were compared with classical beam theory while sandwich theory was applied to the bonded beams as an analytical investigation. As a result of the study, it was found that by reinforcing the adhesive layer using fiber fillers, the flexural stiffness of the bonded beam increased, and as a consequence the bending and the shear stresses are decreased.

Keywords: Adhesive; bonded; epoxy; FE; FRP; structure.

1. INTRODUCTION

Structural adhesives are gaining wide recognition by industry as they offer engineering designers greater flexibility to achieve economic and technical advantages [1]. Relatively thin panels may be braced by steel stiffeners and adhesives avoid the need of welding, where T, L, I, and Z stiffeners are joined to plates. Applications include the marine industry, construction panels and large pipes. Structural epoxy adhesives show good potential in thick applications [2, 3] and the choice of the suitable adhesive is important for good joint performance. Cost effective solution for rehabilitation, strengthening and retrofitting of steel structures such as beams and plates are needed urgently in certain regions and extensive research is progressing in this field. Strengthening and retrofitting is required due to increased service loads, loss of cross-section due to corrosion or other accumulated damage and change in use. Conventional fabrication techniques for retrospective strengthening of steel structures also require heavy equipment for installation. We examined here the use of structural epoxy adhesive to improve the stiffness of laterally loaded beams. Equivalent bonded structural members may be designed to resist lateral loading resulting in direct stresses and shear stress within the adhesive. Very few studies investigated bonded beams under bending but at limited depth [4, 5]. By introducing an interface factor [6] which is defined as ratio between the stresses and deflection values for bonded sections and those of their solid equivalents, the actual in-plane bending and shear stressed for bending of bonded beam might be found.

The aim of the current study is to investigate numerically a beam stiffened by bonding a T-section subjected to lateral load to analyze stresses and deflection in the adhesive layer. In this study it is assumed that the adhesive layer is itself fiber-reinforced. A comparison is made with the previous study [7] which used a pure adhesive layer. Hashim [7] showed through his investigations that using FEM was a powerful tool to estimate and understand the behavior of the adhesively beam. Moreover, he explained that the major problem in studying the bonded beams was prediction the stresses through the adhesive layers, which makes the inspection impossible experimentally, because introducing any measuring transducers will be a stress concentration and as well as consider as a weak spot inside the adhesive layer, so it will cause the unexpected fast failure than the normal condition. So by proving that the experimental results for the global flexural stiffness of the bonded beam is closely coincided with the FE and the theoretical approaches, Hashim concluded and recommended that it is quite enough to use FEM to investigate the other stresses, shear and bending

through the adhesive layer of the bonded beam. Consequently, the present analysis uses the justifications of Hashim [7] to use FEM instead of the experimental procedure to predict numerically the effectiveness of the reinforcing proposed for the bonded layer.

Models representing bonded and welded beam sections; typically 25 mm wide and 20 mm high are produced (Figure 1). The beams with various spans (50–250 mm) are analyzed in three-point bending with simply supported boundary conditions. The study uses classical beam theory, sandwich beam theory and finite element analyses (FEA) techniques.

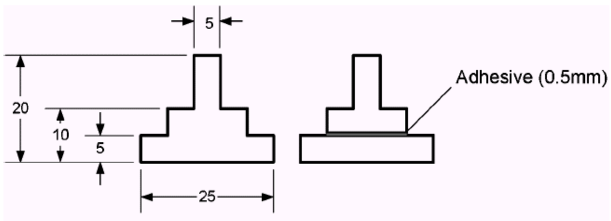


Figure 1. Solid and bonded beam section

2. ANALYTICAL ANALYSIS

Deflection, bending and shear stresses were determined by using classical beam theory for solid structure [8], the bending, shear and deflection used for solid beam section is:

$$\sigma_b = \frac{M.z}{I} \tag{1}$$

$$\tau = \frac{F.Q}{2.I.b} \tag{2}$$

$$\delta = \frac{F.L^3}{48.E_s.I} \tag{3}$$

While sandwich beam theory [9] is applied to the bonded composite beams in which the core is replaced by the adhesive layer, while the upper faces was replaced by the T-stiffeners and the lower face was replaced by a flat plate. The bending, shear and deflection relations for the bonded beam section are:

$$\sigma_b = \frac{M.z.E_s}{D} \tag{4}$$

$$\tau_{\max} = \frac{0.5F.E_s.h.A_s}{D.b} \tag{5}$$

$$\delta_b = \frac{F.L^3}{48.D} + \frac{F.c.L}{G_a.b.d^2.4} \tag{6}$$

For welded and bonded beams, the bending stress is taken at the lower surface of plate, while the shear stress is calculated along the interface between the T-section and the plate, i.e., along the adhesive bond line in the case of the bonded model. The details of the bonded beam are shown in **Figure 2**.

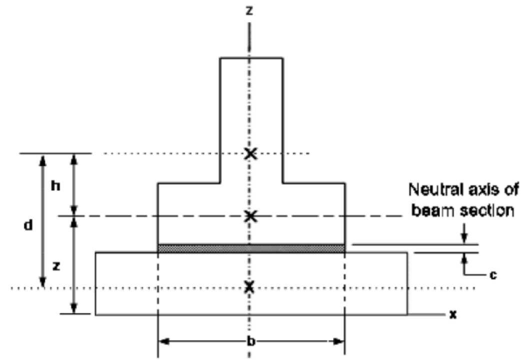
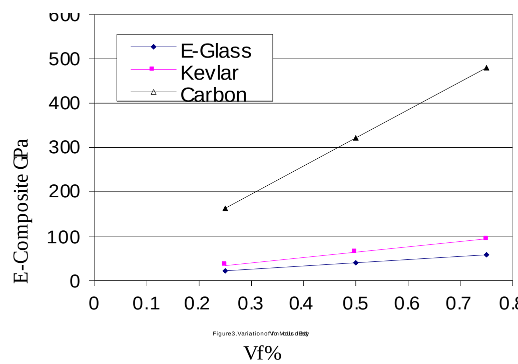


Figure 2. Details of bonded (sandwich) beam section



The interface coefficient may be represented by the ratio between the stresses and deflection values for bonded sections and those of their solid equivalents [6]. Thus, the following general equation for the interface coefficients of deflection, bending stress, and shear stress are used:

$$f_\delta = \frac{\delta_b}{\delta_s},\ f_\sigma = \frac{\sigma_b}{\sigma_s},\ f_\tau = \frac{\sigma_\tau}{\sigma_\tau} \tag{7}$$

The interface coefficient factor can be used for both experimentally and numerically. It is important to mention that measuring of the shear stresses and strain along the bond line is difficult experimentally, but limited for the bending [7]. Therefore FEA is used to estimate the interface coefficient.

3. FILLER REINFORCEMENT MATERIAL

The properties of the adhesive resin are those cited in Loke's earlier study (E=3.5 GPa, μ=0.37) [7]. The reinforced

adhesive layer was assumed to be unidirectional, but for FEA it is considered as an isotropic for simplicity. The modulus computed by the rule of mixtures [10, 11]:

$$E_c = E_f V_f + E_m (1 - V_f) \quad (8)$$

Where E_c, E_f, E_m represent modulus of elasticity of composite adhesive layer, fiber and matrix respectively and V_f is the volume fraction of the fiber. **Table 1** and **Figure 4** show the effect of V_f on the modulus of elasticity for the reinforced adhesive layer. In this study it is assumed using carbon filler for fiber volume fraction of V_f =25% , 50% and 75%.

Table 1. Variation of Modulus of Elasticity with Fiber Volume Fraction V_f% for the reinforced adhesive layer

Modulus of Elasticity GPa			
V_f%	E-Glass	Kevlar	High Modulus Carbon
25	21.6	33.6	162.6
50	39.75	63.7	321.7
75	57.87	93.87	480

4. FINITE ELEMNT SIMULATION

The finite element analysis used ANSYS [12] and the outputs were compared to those of Loke [7]. Predictions were generated of the deflection, shear and bending stresses for solid and reinforced bonded beam of different length which ranged from 250 to 50 mm, all simply supported in three point bending. A 3D 20-node solid element was used in all cases and similar levels of mesh refinement were used in order to obtain consistent analysis, as shown in **Figure 4**. For the steel plate standard values of E=210 GPa and μ=0.3 were applied. A load which produced 90% of the yield stress in the steel plate was applied at mid-span as shown. This was estimated by using the bending beam theory [8] for a solid section.

Due to longitudinal symmetry, one half length of beam was modeled. Deflection at the lower middle span of the beam was recorded, while the bending stresses were taken at the lower surface of the flat plate. The transverse shear stress was estimated along the interface between the plate and the T-section, i.e., along the adhesive bond line in the case of the bonded model. The interface coefficient for the previous study [7] is represented in **Figure 5**, while the results obtained from the present finite element analysis are plotted in **Figures 6** and **Figure 7**.

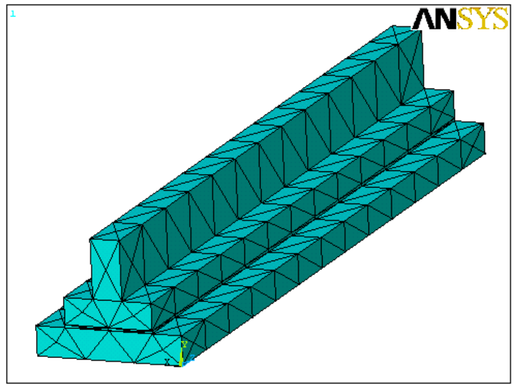


Figure 4. Finite element mesh for half width of the bonded beam model

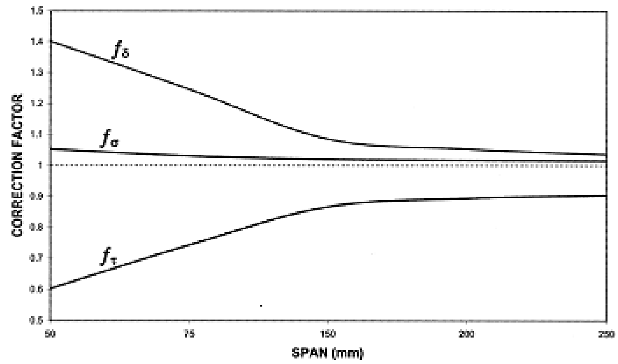


Figure 5. Interface coefficient factor for pure adhesive layer [7]

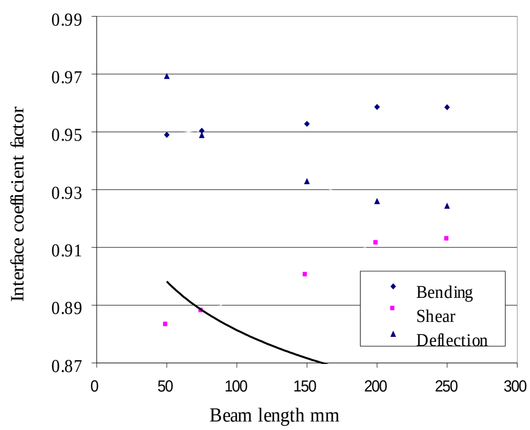


Figure 6. Interface coefficient factor for reinforced adhesive layer (Carbon 25%)

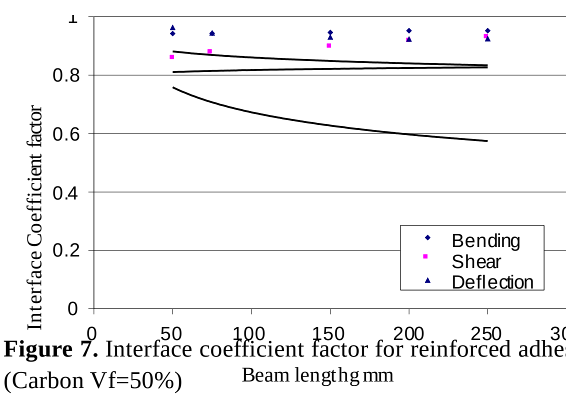


Figure 7. Interface coefficient factor for reinforced adhesive layer (Carbon Vf=50%)

5. CONCLUSIONS

The present study focuses on the investigation of the effectiveness of using fiber reinforcement to improve the mechanical behavior of the adhesively bonded structures which is considered one of the promising sectors. Using FEM was utilized to get closer to understand the overall behavior of the system. The following summery can be concluded for the estimated results.

- It is clear that the adhesively bonded beams (with and without fiber reinforcement) behave differently from their solid (welded) equivalent in terms of their bending and shear stress distributions as well as in their relative flexural stiffness. Simple beam theory therefore has limited accuracy for bonded beams.
- Significant impact of the adhesive reinforcement is shown on the mechanical behavior of the system.
- The results suggest that longer bonded beams behave similarly to their solid counterparts whilst shorter bonded beams exhibit higher bending stresses and deflections than the solid case.
- Shear stresses in bonded beams are significantly lower than for a solid one, depending on span.
- The interface coefficient for small beams could be extended to bonded panel design. Finally, introducing a composite adhesive layer instead of the pure adhesive layer improved the stiffness of the beam and reduces both bending and shear stresses.

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Symbols:

σ_b :maximum bending stress at lower surface of the bonded plate, MPa
δ_b :central deflection of bonded composite beam, mm
τ_{max} :maximum shear stress at the center of the adhesive layer, MPa
D: flexural rigidity of the composite bonded beam, N.mm^2
E_s : Young's modulus of steel, MPa
F: central load, N
G_a : shear modulus of adhesive, MPa
L: span of the beam supports, mm
M: bending moment, N.mm
d: the distance between the centers of the plate and the T section ,mm
b: width of the adhesive layer , mm
c: thickness of adhesive layer, mm
h: distance from neutral axis of the composite beam to the centroid of T section , mm
z: distance from neutral axis of the composite beam to the lower surface of the plate , mm
A_s : section area of T section, mm
Q: First moment of beam section area, mm^3
f_δ :interface coefficient for deflection
f_σ :interface coefficient for bending stress
f_τ :interface coefficient for shear stress
$\sigma_{b:}$ maximum bending stress at lower bonded beam surface, MPa
σ_s : maximum bending stress at lower welded beam surface, MPa
δ_s : central deflection of solid beam, mm
δ_b :central deflection of bonded beam, mm
τ_b :maximum shear stress at the center of the adhesive layer, MPa
τ_s :maximum shear stress of the welded beam at the upper surface of the plate, MPa.

Author Introduction

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